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Kaonic Atoms with the SIDDHARTA-2 Experiment at DAΦNE

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The SIDDHARTA-2 experiment aiming at measuring for the first time the X-ray transitions in kaonic deuterium, has successfully completed its 2024 physics run at the DAΦNE collider of the INFN Laboratori Nazionali di Frascati. This work presents an overview of the scientific and technical achievements of SIDDHARTA-2 so far, including the most precise measurement of kaonic helium-4 L_α transitions and yields in gas, the observation of the kaonic helium-4 M-series transitions, and the measurement of high-n transitions in kaonic carbon, oxygen, nitrogen, and aluminium. The results of these measurements are discussed in the context of the kaonic atoms physics program at DAΦNE, including future prospects within the EXKALIBUR proposal.

topics: kaonic atoms, silicon drift detectors, kaonic deuterium, kaonic helium-4

1. Introduction

Exotic systems have been widely studied for more than 80 years [1], with both leptons [2] and hadrons [3–6], paving the way to the construction of the Standard Model and to a deeper understanding of particle and nuclear physics. The study of hadronic exotic atoms allows reaching low-energy regimes of the strong interaction, which can hardly be probed by scattering experiments. Instead, the hadron–nucleus interaction in exotic systems occurs at very low momentum transfer. In the case of the kaons, the $\bar{K}N$ interaction at the threshold can be directly accessed by kaonic atoms, providing crucial inputs to the understanding of the non-perturbative regime of the strong interaction in the presence of strangeness. Our understanding of this interaction is based on chiral perturbation theory (χPT), however, current implementations utilize various models and approaches, leading to large discrepancies in the prediction of the isospin-dependent antikaon–nucleon scattering lengths [7–19].

Access to the low energy $\bar{K}p$ interaction was provided with great precision by kaonic hydrogen measurements from the SIDDHARTA (SIlicon Drift Detectors for Hadronic Atom Research by Timing Application) experiment [20] in 2009, which enabled the different models to tune their parameters to the experimental data. This was, however, just one of the two main ingredients to completely solve the isospin-dependent ($I = 1,\ 0$) scattering lengths a_0 and a_1.

If $a_{\bar{K}p}$ is expressed as $a_{\bar{K}p} = 1/2(a_0 + a_1)$, and $a_{\bar{K}n} = a_1$, kaonic deuterium data can be used to extract the individual isoscalar a_0 and isovector a_1 scattering lengths, since $a_{\bar{K}d}$ is a function of $a_{\bar{K}p}$ and $a_{\bar{K}n}$.[†1]

Experimentally, the scattering lengths are accessed via the X-ray transitions of the kaonic atoms by extracting the shift ϵ_{1s} defined as

$$\epsilon_{1s} = E_{1s}^{\text{meas.}} - E_{1s}^{EM} \tag{1}$$

and the width Γ_{1s} of the transition $2p \to 1s$ and using the Deser–Trueman formula [21, 22] (modified to take into account isospin breaking corrections).

The SIDDHARTA-2 experiment at the DAΦNE (Double Annular Φ Factory for Nice Experiments) collider of the INFN Laboratori Nazionali di Frascati (INFN-LNF) aims to measure the X-ray transitions in kaonic deuterium, with the goal of reaching a precision of about 30 eV for the shift and 70 eV for the width. The results, coupled with the existing kaonic hydrogen data, will allow the extraction of the antikaon–nucleon isospin 0 and 1 scattering lengths, which are fundamental quantities for understanding the non-perturbative regime of the strong interaction in the presence of strangeness. The aimed accuracy is essential to efficiently disentangle between different theoretical approaches. Currently, more than 800 pb^{-1} of deuterium data have been collected through three dedicated runs, and the data are being calibrated to be analyzed.

In addition to the main scientific objective of the experimental effort, the collaboration has successfully exploited the unique physics opportunities provided by the DAΦNE collider to perform a series of measurements, including the most precise determination of the kaonic helium-4 (KHe-4) L_α transition and yields in gas, the observation of the KHe-4 M-series transitions and the first determination of the high-n transitions in kaonic carbon, oxygen, nitrogen, and aluminium, which we review in this work. Finally, we also briefly comment on the future prospects within the EXKALIBUR (EXtensive Kaonic Atoms research: from LIthium and Beryllium to URanium) proposal.

2. The SIDDHARTA-2 experiment at DAΦNE

The SIDDHARTA-2 experiment is located at the DAΦNE complex at INFN-LNF [23, 24]. DAΦNE is an e^+e^- collider operating at the centre of mass energy of the ϕ resonance (1.02 GeV), which decays with around 48.9% branching ratio to a pair of charged kaons [25]. A unique feature of the DAΦNE collider is the production of almost at-rest kaons, which are emitted mono-energetically ($\Delta p/p = 0.1\%$) with a momentum of 127 MeV/c and can therefore be efficiently stopped in a gaseous target.

The core of the SIDDHARTA-2 setup is a vacuum chamber, hosting the target cell with silicon drift detectors (SDDs) [26–28] to detect the X-rays emitted by the kaonic atoms. These are state-of-the-art radiation detectors for X-rays, with excellent resolution (158 eV FWHM at Fe K_α, where FWHM — full width at half maximum), high efficiency, and large surface area, organized in 48 arrays of eight cells each, developed by Politecnico di Milano, Fondazione Bruno Kessler, Stefan Meyer Institute, and INFN-LNF [29–31]. A series of veto systems for background rejection is installed at the apparatus, comprising VETO-2 [32], located behind the SDDs, and VETO-1 [33] placed around the vacuum chamber. Kaon trigger and luminosity monitor [34] from plastic scintillators [35] are positioned around the interaction region, with the purpose of triggering and luminosity estimation, respectively. A complete overview of the experiment and its operation is given in [36].

[†1] This comes from the relation $a_{\bar{K}d} = \frac{4m_N+m_K}{2m_N+m_K}Q + C$. The factor $Q = 1/2(a_{\bar{K}p} + a_{\bar{K}n}) = 1/4(a_0 + 3a_1)$, and C takes into account the three-body $\bar{K}NN$ interaction.

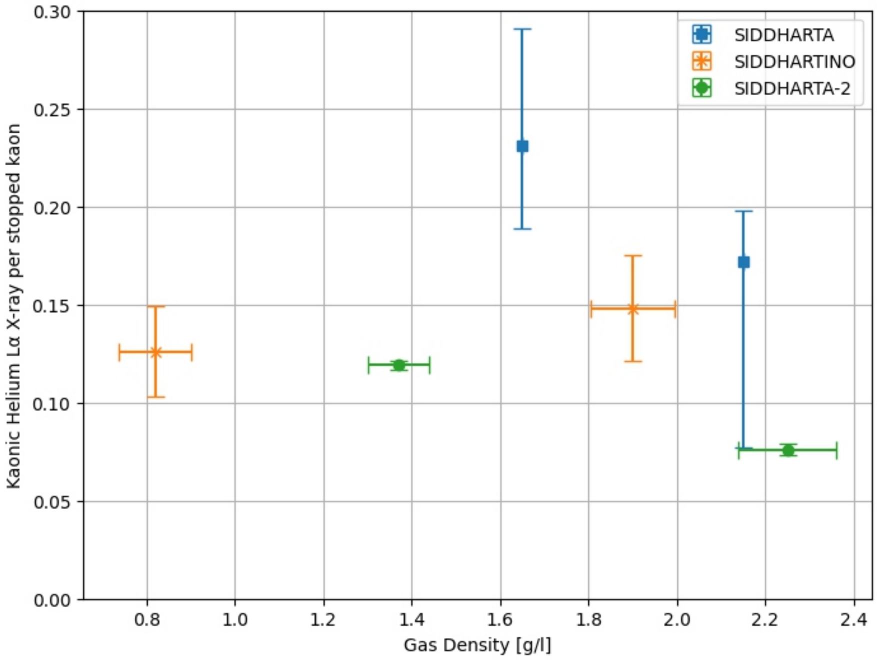

Fig. 1. KHe-4 L_α yields as a function of the gas density. The increasing precision of the measurements is visible as the experiments were upgraded from SIDDHARTA [39] (blue markers) to SIDDHARTINO [38] (orange) and SIDDHARTA-2 [40] (green).

3. Scientific results

In this section, we review the main scientific results obtained so far by the SIDDHARTA-2 experiment.

3.1. Kaonic helium-4 L_α X-ray transitions in a gas target

KHe-4 is characterized by a high yield relative to the lighter kaonic systems and was therefore utilized to optimize the setup and the collider performance in dedicated calibration runs. Apart from a technical utility, KHe-4 has a historical significance in the field of kaonic atoms, and what has attracted interest about it is the shift and width of the transitions induced by the strong interaction and the (absolute) yield of the transition, i.e., the intensity per stopped kaons.

Using 45 pb^{-1} of data, the collaboration performed the most precise measurement in the gas target [37], obtaining

$$\epsilon_{2p} = E^{\text{meas.}}_{3d\to 2p} - E^{EM}_{3d\to 2p} =$$
$$-1.9 \pm 0.8\ (\text{stat}) \pm 2.0\ (\text{sys})\ \text{eV}, \tag{2}$$

$$\Gamma_{2p} = 0.01 \pm 1.60\ (\text{stat}) \pm 0.36\ (\text{sys})\ \text{eV}, \tag{3}$$

which is a confirmation of absence of sharp effects of the strong interaction on the $2p$ level.

TABLE I

Collection of the KHe-4 L_α yield in a gas target, measured by the SIDDHARTA, SIDDHARTINO, and SIDDHARTA-2 experiments.

Gas density [g/l]	KHe-4 L_α yield	Reference
0.82 ± 0.082	0.126 ± 0.023	SIDDHARTINO [38]
1.37 ± 0.07	0.119 ± 0.002	SIDDHARTA-2 [37]
1.65	$0.231^{+0.060}_{-0.042}$	SIDDHARTA [39]
1.90 ± 0.095	0.148 ± 0.027	SIDDHARTINO [38]
2.15	$0.172^{+0.026}_{-0.095}$	SIDDHARTA [39]
2.25 ± 0.11	0.076 ± 0.003	SIDDHARTA-2 [40]

Using the same data, the first measurement of the M-series transitions was reported together with their absolute and relative yields [37]. The energies of the measured M-series are

$$E_{M_\beta} = 3300.8 \pm 13.2\ (\text{stat}) \pm 2.0\ (\text{sys})\ \text{eV}, \tag{4}$$

$$E_{M_\gamma} = 3860.4 \pm 13.6\ (\text{stat}) \pm 2.2\ (\text{sys})\ \text{eV}, \tag{5}$$

$$E_{M_\delta} = 4214.1 \pm 19.6\ (\text{stat}) \pm 2.2\ (\text{sys})\ \text{eV}. \tag{6}$$

Finally, we compile a collection of the KHe-4 L_α yield in gas target, measured by the SIDDHARTA, SIDDHARTINO[†2], and SIDDHARTA-2 experiments in Table I [37–40]. The results are shown in Fig. 1. These measurements are of fundamental importance for the understanding of the de-excitation mechanism in kaonic atoms, in terms of testing and development of cascade models [41–43]. As visible in Fig. 1, the point at 2.25 g/l suggests a reduction of the yield, which is an expected indication of the Stark effect, which increases the kaon nuclear absorption from higher energy levels.

3.2. High-n transitions in intermediate mass kaonic atoms

Higher-n transitions in kaonic atoms have the potential to further constrain the theoretical description of the $\bar{K}N$ interaction, serving as a database for low-energy QCD interaction in the presence of strangeness. However, past data, if available [44], are affected by large uncertainties, and several experimental results were proven to be at variance with more recent measurements employing modern detector technology. In SIDDHARTA-2, kaons entering the cryogenic target can form kaonic atoms with the apparatus' material, leading to the emission of X-rays from the transitions in the intermediate mass kaonic atoms. The collaboration has performed the first measurements of high-n transitions in kaonic carbon, oxygen, nitrogen, and aluminium, which are reported in [45] and reproduced here in Table II.

4. Future opportunities and the EXKALIBUR proposal

In this section, we report on the future prospects of the SIDDHARTA-2 experiment, which are summarized in the EXKALIBUR proposal [46], articulated in its first stage in three sets of measurements.

In the first one, the collaboration plans to use 300 pb^{-1} of integrated kaonic neon data for a measurement of the kaon mass and quantum electrodynamics (QED) studies with below 1 eV precision. High-n transitions in kaonic neon can experimentally access the kaon mass, which so far is plagued by a large uncertainty derived by the incompatibility of the two most precise existing measurements [47].

The second (kaonic Be, B, Li) low-Z set of measurements will study in detail the $\bar{K}NN$ in the nuclear medium, which at present can only partially describe the kaonic data from old experiments with ad-hoc phenomenological terms. New precision measurements using 200 pb^{-1} could greatly benefit more advanced descriptions making use of optical potential linked to the kaon interaction with more than one nucleon.

TABLE II

Transition energies with statistical and systematic uncertainties for various transitions [45].

Transition	Energy [eV]
K$^-$C ($6 \to 5$)	5541.7 ± 3.1 (stat) ± 2.0 (sys)
K$^-$C ($7 \to 5$)	8890.0 ± 13.0 (stat) ± 2.0 (sys)
K$^-$C ($5 \to 4$)	10216.6 ± 1.8 (stat) ± 3.0 (sys)
K$^-$C ($6 \to 4$)	15760.3 ± 4.7 (stat) ± 12.0 (sys)
K$^-$O ($7 \to 6$)	6016.0 ± 60.0 (stat) ± 2.0 (sys)
K$^-$O ($6 \to 5$)	9968.1 ± 6.9 (stat) ± 2.0 (sys)
K$^-$N ($6 \to 5$)	7577.0 ± 17.0 (stat) ± 2.0 (sys)
K$^-$N ($5 \to 4$)	14010.6 ± 8.2 (stat) ± 9.0 (sys)
K$^-$Al ($8 \to 7$)	10441.0 ± 8.5 (stat) ± 3.0 (sys)
K$^-$Al ($7 \to 6$)	16083.4 ± 3.8 (stat) ± 12.0 (sys)

In the same spirit, a third (kaonic O, Al, S) set of measurements can be performed, in parallel with the previous ones, with CdZnTe detectors because of the higher energy of their transitions (30–300 keV).

5. Conclusions

In this paper, we reported the main scientific results obtained so far by the SIDDHARTA-2 experiment at the DAΦNE collider of the INFN Laboratori Nazionali di Frascati. The experiment successfully completed its physics run in June 2024, collecting more than 800 pb^{-1} of kaonic deuterium data, which are ready to be analyzed. It has performed a series of measurements, including the most precise determination of the KHe-4 L_α transition and yields in gas, the first observation of the KHe-4 M-series transitions, and a precision measurement of the high-n transitions in kaonic carbon, oxygen, nitrogen, and aluminium. The results of these measurements were discussed in the context of the kaonic atoms physics program at DAΦNE and the future prospects represented by the EXKALIBUR proposal.

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[†2] SIDDHARTINO was a reduced, pilot version of the SIDDHARTA-2 apparatus.

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